LED CURING APPARATUS AND METHOD

Background Of The Invention

Related Application

The present application is related to co-owned and concurrently filed U.S. Patent application entitled "Solid State Light Device" (Atty. Docket No. 59349US002), incorporated by reference herein in its entirety. The present application is also related to co-owned and concurrently filed U.S. Patent applications entitled "Reflective Light Coupler" (Atty. Docket No. 59121US002); "Illumination System Using a Plurality of Light Sources" (Atty. Docket No. 58130US004); "Multiple LED Source and Method for Assembling Same" (Atty. Docket No. 59376US002); "Illumination Assembly" (Atty. Docket No. 59333US002), "Phosphor Based Light Sources Having a Polymeric Long Pass Reflector" (Atty. Docket No. 58389US004); and "Phosphor Based Light Sources Having a Non-Planar Long Pass Reflector" (Atty. Docket No. 59416US002) each of which is incorporated by reference herein in its entirety.

Field of the Invention

The present invention relates to a curing apparatus, system, and method. More particularly, the present invention relates to a solid state light device, system, and method that may replace current high intensity directed light sources and techniques that are used for curing applications.

Background Art

Illumination systems are used in a variety of applications. Home, medical, dental, and industrial applications often require light to be made available. Similarly, aircraft, marine, and automotive applications often require high-intensity illumination beams.

Traditional lighting systems have used electrically powered filament or arc lamps, which sometimes include focusing lenses and/or reflective surfaces to direct the produced illumination into a beam. Conventional light sources based on powered filament or arc lamps, such as incandescent or discharge bulbs, radiate both heat and light in 360 degrees. Conventional sources also include microwave-driven sources. Thus, for traditional applications, the optics used must be designed and/or specially treated to withstand the constant heating effects caused by the high intensity (and high heat) discharge bulbs. In addition, expensive and complicated heat transfer systems must be employed if heat is to be removed from the area of illumination.

For example, conventional curing systems utilize water chill rolls to minimize distortion and/or destruction of the substrate and/or the formulation. Other conventional systems utilize a flat water chill plate located just below or in contact with the substrate.

For curing applications, stacked-LED arrays are now being investigated (e.g., arrays that can be "stacked" in a cross-machine-direction (CMD) and machine-direction (MD) manner). With these conventional systems, however, the irradiance and lifetime drop quickly as the LED emission wavelengths get shorter. This may lead to problems with initiating chemical reactions via radiation absorption and response by photoinitiators, which are typically formulated to absorb radiation less than 450 nm. If the irradiance is too low, it is possible that the polymerization reaction would not yield desired product properties.

To counteract low irradiance, a conventional technique is to position LEDs close to one another to increase the overall irradiance and attain desired cure. However, arranging the LEDs in such a manner results in several complications relating to thermal management and electrical connections. If the LEDs are more spread out, irradiance uniformity across the array can become non-ideal. Reflectors are sometimes mounted around the LEDs to improve irradiance levels, but this approach still suffers from non-uniformity across the reflector opening. If an appropriate material is not used within the reflector, the irradiance will also drop by the square of the distance to the irradiated surface.

Summary Of The Invention

In accordance with a first embodiment of the present invention, a radiation curing apparatus comprises a plurality of solid state radiation sources to generate radiation. The solid state radiation sources can be disposed in an array pattern. Optical concentrators, arranged in a corresponding array pattern, receive radiation from corresponding solid state radiation sources. The concentrated radiation is received by a plurality of optical waveguides, also arranged in a corresponding array pattern. Each optical waveguide includes a first end to receive the radiation and a second end to output the radiation. A support structure is provided to stabilize at least a first portion of the second ends of the plurality of optical waveguides.

In exemplary embodiments, the light sources are individual LED dies or chips, or laser diodes. The waveguides may include optical fibers, such as polymer clad silica fibers, silica fibers, or other types of fibers to transmit the selected wavelength(s) of radiation. The first ends of the plurality of optical waveguides receive the light emitted from the light sources. The second ends of the plurality of optical waveguides may be bundled or arrayed to form a single light emission source when illuminated.

The optical concentrators can be non-imaging optical concentrators, such as reflective couplers, that couple and concentrate light emitted from the radiation sources to provide useable emission to be guided through the corresponding optical waveguides. In an exemplary embodiment, each optical concentrator is in optical communication with and interposed between a corresponding LED die and a first end of a corresponding optical waveguide.

According to another embodiment of the present invention, a method of curing a radiation curable chemical formulation comprises providing a solid state radiation source that includes a plurality of LED dies to generate curing radiation. A plurality of optical concentrators receives curing radiation from a corresponding one of the LED dies. A plurality of optical fibers, each having a first end and a second end, is also provided, where each first end receives concentrated curing radiation from a corresponding concentrator. The method further includes exposing the radiation-curable chemical formulation to the curing radiation, where a substrate supports the radiation-curable chemical formulation.

The above summary of the present invention is not intended to describe each illustrated embodiment or every implementation of the present invention. The figures and the detailed description that follow more particularly exemplify these embodiments.

Brief Description Of The Drawings

Fig. 1A shows a perspective view and Fig. 1B shows an exploded view of a solid state light device according to an exemplary embodiment of the present invention.

Fig. 2 shows a top view of an exemplary LED die array disposed on an interconnect circuit according to an embodiment of the present invention.

Fig. 3 shows a side view of a solid state light source according to an embodiment of the present invention.

Fig. 4 shows a close-up view of an individual LED die coupled to an optical fiber by a non-imaging optical concentrator according to an embodiment of the present invention.

Figs. 5A-5F show alternative fiber output patterns according to alternative embodiments of the present invention.

Fig. 6A shows an alternative fiber output pattern for a steerable output and Figs. 6B and 6C respectively show exemplary banding and support structure implementations for a steerable output in accordance with alternative embodiments of the present invention.

Fig. 7 shows another alternative output pattern for a steerable output, where a portion of the output ends of the fibers have angle polished output faces in accordance with an alternative embodiment of the present invention.

Fig. 8 shows an alternative construction for a fiber array connector in accordance with an embodiment of the present invention.

Fig. 9A shows a solid state lighting system adapted for pixelation in accordance with another embodiment of the present invention.

Fig. 9B shows an exemplary controller circuit adapted for pixelation in accordance with another embodiment of the present invention.

Fig. 10 shows an exemplary implementation of the solid state light device.

Fig. 11 shows another exemplary implementation of the solid state light device, here utilized as part of a dental curing apparatus.

Fig. 12 shows a radiation curing apparatus according to another exemplary embodiment of the present invention.

Fig. 13 shows an alternative embodiment for a steerable output emission.

While the invention is amenable to various modifications and alternative forms, specifics thereof have been shown by way of example in the drawings and will be described in detail. It should be understood, however, that the intention is not to limit the invention to the particular embodiments described. On the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the appended claims.

Detailed Description

Fig. 1A shows a solid state light device 100 (also referred to herein as an illumination device or photon emitting device) in an exemplary configuration. Light device 100 is shown in an exploded view in Fig. 1B. By "light" it is meant electromagnetic radiation having a wavelength in the ultraviolet, visible, and/or infrared portion of the electromagnetic spectrum. In the construction described below, the light device 100 can have an overall compact size comparable to that of a conventional High Intensity Discharge (HID) bulb, thus providing a replacement for a discharge lamp device in various applications including road illumination, spot lighting, back lighting, image projection and radiation activated curing.

Light device 100 comprises an array of solid state radiation sources 104 to generate radiation. The radiation is collected and concentrated by a corresponding array of optical concentrators 120. The concentrated radiation is then launched into a corresponding array of waveguides 130, which are supported by a support structure 150. Each of these features will now be described in more detail.

In an exemplary embodiment, the solid state radiation sources 104 comprise a plurality of discrete LED dies or chips disposed in an array pattern. The discrete LED dies 104 are mounted individually and have independent electrical connections for operational control

(rather than an LED array where all the LEDs are connected to each other by their common semiconductor substrate). LED dies can produce a symmetrical radiation pattern and are efficient at converting electrical energy to light. As many LED dies are not overly temperature sensitive, the LED dies may operate adequately with only a modest heat sink compared to many types of laser diodes. In an exemplary embodiment, each LED die is spaced apart from its nearest neighbor(s) by at least a distance greater than an LED die width. In a further exemplary embodiment, each LED die is spaced apart from its nearest neighbor(s) by at least a distance greater than six LED die widths. These exemplary embodiments provide for suitable thermal management, as explained in further detail below.

In addition, LED dies 104 can be operated at a temperature from –40° to 125°C and can have operating lifetimes in the range of 100,000 hours, as compared to most laser diode lifetimes around 10,000 hours or halogen automobile headlamp lifetimes of 500-1000 hours. In an exemplary embodiment, the LED dies can each have an output intensity of about 50 Lumens or more. Discrete high-power LED dies can be GaN-based LED dies commercially available from companies such as Cree (such as Cree's InGaN-based XBright™ products) and Osram. In one exemplary embodiment, an array of LED dies (manufactured by Cree), each having an emitting area of about 300 μm x 300 μm, can be used to provide a concentrated (small area, high power) light source. Other light emitting surface shapes such as rectangular or other polygonal shapes can also be utilized. In addition, in alternative embodiments, the emission layer of the LED dies utilized can be located on the top or bottom surface.

In some exemplary embodiments, a plurality of bare blue or ultraviolet (UV) LED dies can be utilized. In alternative embodiments, one or more LED dies can be coated, preferably on a light-emitting surface, with a phosphor layer (not shown), such as YAG:Ce phosphor for the blue LED die, or a mixture of RGB (red, green, blue) phosphors utilized with a UV LED die. Thus, the phosphor layer can be used to convert the output of the LED die into "white" light under different mechanisms. Phosphor layer placement and construction is described in detail in a co-owned and concurrently filed application entitled "Illumination System Using a Plurality of Light Sources" (Atty. Docket No. 58130US004), incorporated by reference above.

In an alternative embodiment, a collection of red, blue, and green LED dies can be selectively placed in an array. The resulting emission is collected by the array of fibers 130 so that the light emitted from the output ends of the fibers is seen by an observer as colored light or "white" light, when blended together in concert.

In an alternative embodiment, the LED die array may be replaced with a vertical cavity surface emitting laser (VCSEL) array, which can conventionally provide output in the visible region, including "white" light.

As shown in Fig. 1B, the emission from LED dies 104 is received by a plurality of optical concentrators 120 which are disposed in a corresponding array pattern. In an exemplary embodiment, each optical concentrator receives radiation from a corresponding one of the LED dies 104. In an exemplary embodiment, the optical concentrators 120 comprise non-imaging optical concentrators (also referred to as reflective optical couplers) disposed in an array. The shape of the reflective surfaces of the optical concentrators 120 are designed to capture a substantial portion of the radiation emitted by each of the sources 104 to preserve the power density. In addition, the concentrated output can be designed in a manner to substantially match the acceptance angle criteria of the light receiving waveguides, so that a substantial portion of the radiation is useably captured by the waveguides 130 and guided therethrough. In an exemplary embodiment, each non-imaging concentrator of the array of non-imaging concentrators 120 has an interior reflecting surface conforming to a two-dimensional (2-D) surface, with at least a second portion of the interior reflecting surface conforming to a three-dimensional (3-D) surface. This and other reflective surface designs are described in detail in the commonly owned and co-pending patent application entitled "Reflective Light Coupler" (Atty. Docket No. 59121US002), filed concurrently, and incorporated by reference herein in its entirety.

Each optical concentrator in array 120 can be formed by, e.g., injection molding, transfer molding, microreplication, stamping, punching or thermoforming. The substrate or sheeting in which the optical concentrators 120 can be formed (singularly or as part of an array of optical concentrators) can include a variety of materials such as metal, plastic, thermoplastic material, or multilayer optical film (MOF) (such as Enhanced Specular

Reflector (ESR) film available from 3M Company, St. Paul, MN). The substrate material used to form the optical concentrator 120 can be coated with a reflective coating, such as silver, aluminum, or reflective multilayer stacks of inorganic thin films, or simply polished in order to increase its reflectivity.

In addition, the optical concentrator substrate can be disposed so that the array of optical concentrators can be oriented beneath, around, or above the LED dies. In an exemplary embodiment, the optical concentrator substrate is disposed on or proximate to the LED array so that each concentrator of array 120 can be formed to slide over each LED die 104, so that the optical concentrator's lower opening 123 (see Fig. 4) provides a close fit around the perimeter of the LED die 104. Alternative concentrator designs include the additional use of a reflective coating on the substrate on which the LED die is supported.

An aspect of the illustrated embodiment of Fig. 1B is the one-to-one correspondence between each radiation source, a corresponding optical concentrator, and a corresponding waveguide. Each optical concentrator surface is designed to convert the isotropic emission from a corresponding LED die, which can be a phosphor-coated LED die in some applications, into a beam that will meet the acceptance angle criteria of a corresponding light-receiving waveguide. As stated above, this concentrator surface design aids in preserving the power density of the light emitted from the LED dies.

Referring back to Fig. 1B, the concentrated output radiation is received by a plurality of optical waveguides 130, shown in Fig. 1B as an array of optical fibers, with each waveguide having an input end 132 and an output end 133. The present exemplary embodiment includes an array 130 of large-core (for example, 400 μm to 1000 μm) polymer clad silica fibers (such as those marketed under the trade designation TECS™, available from 3M Company, St. Paul, MN). In a further exemplary embodiment, each of the optical fibers 130 can comprise polymer clad silica fibers having a core diameter of about 600 μm to 650 μm. In exemplary embodiments, the longitudinal lengths of the fibers can be about 1 to 5 inches (2.5 cm – 12.5 cm) in length. As the exemplary fibers are very flexible, this short distance still provides the ability to place the fibers in a tight, patterned bundle at the output ends. In addition, the short length provides for a very compact device having a size

comparable to the size of conventional HID lamps. Of course, the fiber lengths can be increased in other applications without causing a detrimental effect in output.

Other types of optical fibers, such as conventional or specialized silica fibers may also be utilized in accordance with the embodiments of the present invention, depending on such parameters as, e.g., the output wavelength(s) of the LED die sources. For example, polymeric fibers may be susceptible to solarization and/or bleaching with applications involving deep blue or UV light sources. In the present exemplary embodiments, based on the type of photo-initiator or other curable material to be irradiated, optical fibers/waveguides that provide low losses for wavelengths of 450 nm or less can be utilized.

Alternatively, as would be apparent to one of ordinary skill given the present description, other waveguide types, such as planar waveguides, polymer waveguides, flexible polymer waveguides, or the like, may also be utilized in accordance with the present teachings.

Once the light emitted by the LED die is collected and redirected by the concentrator into the light-receiving fiber, the fiber(s) can be used to transport the light to a specific location with low optical loss by total internal reflection. However, the light receiving fibers do not only serve to transport light - by translating the fibers from the wider spacing of the LED die array to a tighter spacing or spacings at the output aperture, such as a tight packed fiber bundle, light from the (relatively) dispersed LED array can be effectively concentrated into a very small area. Also, the optical design of the exemplary light receiving fiber core and cladding provide for shaping the light beams emerging from the bundled ends due to the Numerical Aperture (NA) of the fibers at the input end as well as the output end. As described herein, the light receiving fibers perform light concentrating and beam shaping, as well as light transportation.

The optical fibers 132 may further include fiber lenses on one or more of the output ends 133 of the optical fibers. Similarly, the light receiving ends 132 of the optical fibers 130 may each further comprise a fiber lens. Fiber lens manufacture and implementation is described in commonly owned and co-pending U.S. Patent Application Nos. 10/317,734 and 10/670,630, incorporated by reference herein. Alternatively, a continuous optical element,

such as a lens, can be placed across the fiber array to focus, diffuse, or collimate the irradiance.

A fiber array connector 134 can be utilized to support the first ends of each optical fiber of array 130. In an exemplary embodiment, the fiber array connector 134 comprises a rigid material, such as a molded plastic material, with a plurality of apertures having a pattern corresponding to the pattern of optical concentrators 120. Each aperture receives the input end 132 of an optical fiber of array 130 and can provide for straightforward bonding thereto.

In an exemplary embodiment, an interconnect circuit layer, rigid or flexible, can be utilized to provide thermal management for and electrical connection to the LED dies 104. As shown in Fig. 1B, the interconnect circuit layer can comprise a multilayer structure, such as 3M™ Flexible (or Flex) Circuits, available from 3M Company, Saint Paul, MN. For example, the multilayer interconnect layer can comprise a metal mounting substrate 112, made of e.g., copper or other thermally conductive material, an electrically insulative dielectric layer 114, and a patterned conductive layer 113, where the LED dies are operatively connected to bond pads (not shown) of the conductive layer 113. Electrically insulative dielectric layer 114 may comprise of a variety of suitable materials, including polyimide, polyester, polyethyleneterephthalate (PET), polycarbonate, polysulfone, or FR4 epoxy composite, for example. Electrically and thermally conductive layer 113 may comprise of a variety of suitable materials, including copper, nickel, gold, aluminum, tin, lead, and combinations thereof, for example.

In an exemplary embodiment, and as described in more detail below, one or more groups of the LED dies 104 are interconnected with each other, but separate from other groupings of LED dies, to provide for pixelated radiation output. Vias (not shown) can be used to extend through the dielectric layer 114. The metal mounting substrate 112 can be mounted on a heat sink or heat dissipation assembly 140. The substrate 112 can be separated from heat sink 140 by a layer 116 of electrically insulative and thermally conductive material. In an exemplary embodiment, heat sink 140 can further comprise a series of thermal conductor pins to further draw heat away from the LED die array during operation.

In one exemplary embodiment, each bare LED die 104 can reside in a recessed portion of the dielectric surface 114, directly on the metal/circuit layer 113. Example implementations of interconnect circuitry are described in a currently pending and co-owned application entitled "Illumination Assembly" (Atty. Docket No. 59333US002), incorporated by reference herein in its entirety.

In another embodiment, a more rigid FR4 epoxy based printed wiring board structure can be utilized for electrical interconnection. In yet another embodiment, a low cost circuit can be prepared by patterning conductive epoxy or conductive ink onto a suitable substrate as required to connect the LED die array.

Solid state light device 100 further includes a support structure. In the exemplary embodiment of Fig. 1B, the support structure is configured as a housing 150, having an input aperture 152 and an output aperture 154. The housing 150 provides strain relief for the array of waveguides 130 and can prevent damage to the waveguides 130 from outside sources. In addition, housing 150 can provide a rigid support that is preferred for vehicular applications, such as those described in more detail below. Optionally, when waveguides 130 are optical fibers, the support structure can further include a banding 156 that is disposed in contact with a perimeter portion of the second ends of waveguides 130. The banding 156 can aid in distributing the output ends 134 of waveguides 130 in a selected output pattern, as is described in further detail below.

In addition, the fiber array connector 134 can include a ridge or indentation to receive the input aperture 152 of housing 150. While the housing 150 may be bonded or otherwise attached to fiber array connector 134, in an exemplary embodiment, the housing 150 is snap fit on fiber array connector 134.

In an exemplary construction method, the fibers are first loaded into the fiber array connector and bonded to the connector. A fixture (not shown) can be utilized to group fibers in rows to have an ordered grouping. The fixture can comprise multiple partitions that repeatably position each fiber from the input end to the output end. In addition, the fixture can be designed so that the fibers do not cross over one another and have a predictable location for the output ends. To secure the output end, a rigid or flexible banding, e.g. a

polymer material, is utilized to fix the location of the fibers within a desired output pattern. The strain relief/support housing can then be slid over the fibers and banding and secured to the fiber array connector. The banding can be secured within the output aperture of the housing through the use of conventional adhesives or bonding elements. Alternatively, the support structure can comprise an encapsulate material that is formed throughout and around the fiber bundle(s).

Alternatively, support structure 150 can comprise an adhesive material, such as a binding epoxy, which can be applied to a portion of the waveguides 130, such that when the adhesive sets, the waveguides are fixed in a desired pattern.

Overall alignment can be provided by one or more alignment pins 160, which can be used to align the fiber array connector 134, concentrator array 120, interconnect circuit layer 110 and heat sink 140 together. A series of alignment holes, such as alignment holes 162 shown in Fig. 2, can be formed in each of the aforementioned parts of the device 100 to receive the alignment pins 160. Alignment of the optical concentrator array 120 to the interconnect circuit layer can be accomplished through the use of fiducials (not shown).

Fig. 2 illustrates the footprint of the solid state light device 100. In this exemplary configuration, an array of sixty (60) LED dies 104 can be provided on an interconnect circuit layer 110, which is mounted on heat sink 140, in a substantially rectangular array pattern. Of course, in accordance with the present invention, the array of LED dies can comprise a substantially greater or lesser number of LED dies 104. However, as each LED die has a width of about 300 micrometers, and each LED die 104 can be spaced from its nearest neighbor by more than a LED die width, the solid state light source of the present invention can provide a high overall power density, a compact footprint area (about 1 in^2 to 4 in^2, or 6.5 cm^2 to 26 cm^2) and adequate thermal control. In addition, the footprint of the output ends of the fibers 133 (see Fig. 1B) can be even more compact, for example, on the order of about 0.1 in^2 to 1 in^2 (0.65 cm^2 to 6.5 cm^2), in exemplary embodiments. Alternatively, the footprint of the output ends may be much longer in one direction over another, such as is shown in one or more of the embodiments described below.

A side view of solid state light device 100 is shown in Fig. 3. In this exemplary embodiment, interconnect circuit layer 110 (having LED dies mounted thereon) is disposed on heat sink 140, which further includes heat dissipation pins 142 that extend in an opposite direction from the output aperture 154. In addition, as described above, the housing 150 can include protrusions 153 to allow for snap fitting onto fiber array connector 134. The array of optical concentrators 120 is disposed between the fiber array connector 134 and the interconnect layer 110. In this embodiment, fibers 130 are supported by the fiber array connector 134 and the banding 156, which is disposed within the output aperture 154 of housing 150.

As shown in greater detail in Fig. 4, an exemplary construction of the solid state light device includes a fiber-concentrator alignment mechanism that reduces misalignment between an individual optical fiber 131 of the fiber array and an individual optical concentrator 121 of the concentrator array. In particular, the fiber array connector 134 can further include a protrusion portion 135 that engages in a depression portion 125 of the optical concentrator array substrate. Thus, fiber 131 is received in an aperture of the fiber array connector 134. The fiber array connector is then disposed on the optical concentrator substrate such that protrusion 135 is received by depression 125. In this manner, the output aperture 126 of optical concentrator 121 can be substantially flush with the input end of fiber 131. In addition, with this exemplary design, multiple input ends of the fibers can be polished at the same time so that the fiber ends are positioned with respect to the optical concentrators.

In the example construction of Fig. 4, the receiving aperture 123 of optical concentrator 121 can be disposed to be proximate to or to surround the perimeter of an emission surface of a corresponding LED die 104. Although not shown, spacers located between the optical concentrator substrate and the interconnect circuit layer can set the proper spacing between these two components. The optical concentrator substrate can then be affixed to the spacers or otherwise bonded to the interconnect circuit layer using conventional techniques.

Fig. 4 further shows a cross section of an exemplary multiple layer interconnect 110, which comprises a conductive epoxy 115 to bond LED die 104 to interconnect layer 110.

First and second electrically conductive layers 113, 111 (that can comprise, e.g., nickel and gold, or other conductive materials), provide electrical traces to each LED die in the array, with dielectric layer 114 (e.g., polyimide) disposed to provide electrical insulation. A substrate 112 (e.g., copper) is provided to support the conductive and insulating layers, as well as to provide thermal conductivity to the heat sink 140 to conduct heat away from the direction of emission.

In accordance with the principles described herein, the solid state light device can provide a highly directional and/or shaped output emission, in one or more directions simultaneously. As shown in Figs. 1A and 1B, the output ends 133 of fiber array 130 can be patterned to provide a rectangular or square output. Figs. 5A-5F illustrate alternative reconfigurable output end patterns for the fiber array that can be employed depending on the type of illumination that is required for a particular application. For example, Fig. 5A shows a hexagonal output fiber pattern 133A, Fig. 5B shows a circular output fiber pattern 133B, Fig. 5C shows a ring-shaped output fiber pattern 133C, Fig. 5D shows a triangular output fiber pattern 133D, and Fig. 5E shows a line-shaped output fiber pattern 133E. In addition, as shown in Fig. 5F, in an alternative exemplary embodiment, a segmented output pattern 133F can be provided, where multiple separate fiber output groupings can be utilized for specific targeted illumination. As the banding that secures the output ends of the fibers can be formed from a material with flexibility, such as lead, tin, and zinc-based materials and alloys, in some applications, the fiber output pattern can be reconfigurable.

As shown in Figs. 6A-6C, the output of the solid state light device can be steerable, so that one or more different directions can be illuminated simultaneously or alternatively. Fig. 6A shows fiber output ends 233 arranged, e.g., in three different groupings, 233A, 233B, and 233C. For example, the solid state light device can provide output illumination in a forward direction through output ends 233A under normal operation. In the event of a trigger signal, the LED dies that correspond to the output fibers 233B can be activated so that additional illumination can be provided in that side direction through output fibers 233B. Similarly, the LED dies which correspond to the output fibers 233C can be activated so that additional illumination can be provided in that other side direction.

In curing applications, such as described below with respect to Fig. 12, the "steering" of the fiber output can facilitate radiation curing of complex three-dimensional parts and structures. These types of structures are not well suited for "flood"-type curing with conventional sources, as shadowing effects result in non-uniform curing. In addition, conventional arrays of packaged LEDs arranged on rigid circuit boards are not easily bent to accommodate complex shapes.

Alternatively, a steerable illumination system can be provided utilizing a laterally extended output arrangement of fibers, such as shown in Fig. 5E, whereby the pixelation control circuitry described below (see e.g., Figs. 9A and 9B) can activate blocks of illuminated fibers from one side to the other. In this manner, the output illumination can be directed towards (or away from) a particular direction, depending on the application.

In this manner, a non-mechanical approach can be used to provide steerable output illumination from the solid state light device. Alternatively, as would be apparent to one of ordinary skill in the art given the present description, greater or fewer fiber groupings can be utilized. In addition, the groupings can have a different relative orientation.

In Fig 6B, a construction is shown that can be utilized to stabilize and support the different fiber groupings. For example, a banding 256 is provided at the output ends of the optical fibers. The banding 256 can provide a first aperture 254, a second aperture 254A and a third aperture 254B, where the fibers disposed in apertures 254A and 254B will output light in different directions from the fibers disposed in aperture 254. In addition, as shown in Fig. 6C, the banding 256 can be connected to or integral with housing 250, as part of the support structure for the solid state light device.

Alternatively, as shown in Fig. 7, the solid state light device can generate steerable light from a single bundle of fiber output ends. For example, fiber output ends 133 can be provided in the same location, such as output aperture 254 from Fig. 6B. In this exemplary embodiment, a portion of these output ends, identified as fiber output ends 129, are angle polished at a different angle, or even substantially different angle (e.g., by 10 to 50 degrees with respect to the fiber axis), than the remainder of fiber output ends 133. The resulting emission will be directed in a different direction from that of the output of fiber ends 133.

Thus, similar to the application discussed above with respect to Figs. 6A-6C, the solid state light device can provide output illumination in a both a forward direction (through output ends 133) and a side direction (through output fibers 129).

In an alternative embodiment to provide steerable illumination, illustrated in Fig. 13, fibers extending from fiber array connector 734 can be bundled into multiple offset fiber bundles, central bundle 730A and side bundles 730B and 730C. Light emitted by the output ends of the fiber bundles is received by a multi-focus lens 750, such as an aspheric lens, that further directs the output from the offset bundles into desired different illumination regions 751A, 751B, and 751C.

In an exemplary embodiment of the present invention, the solid state light device can be utilized as a bulb replacement for a discharge-type illumination source. For example, attachment to an existing receptacle can be accomplished through the use of flanges 139, shown in Fig. 8. Flanges 139 can be disposed on the perimeter portion of e.g., the fiber array connector 134. The flange can be designed to engage in a locking slot of such a receptacle. Alternatively, the flanges may be formed on other components of the solid state light device, such as the housing or optical concentrator substrate.

According to another embodiment of the present invention, as shown in Fig. 9A, an illumination system 300 is provided that allows for pixelated light control that can be used for aperture shaping and/or dynamic beam movement. System 300 includes a solid state light source 301 that is constructed in a manner similar to solid state light source 100 described above. A controller 304 is coupled to solid state light source 301 via wiring 302 and connector 310, which can be connected to the interconnect circuit layer. A power source 306 is coupled to the controller 304 to provide power/current to the solid state light source 301.

In an exemplary embodiment, controller 304 is configured to selectively activate individual LED dies or groups of LED dies that are contained in solid state light source 301. In addition, as the light receiving waveguides are provided in a one to one correspondence with the LED dies, the illumination system 300 can provide a pixelated output. This type of pixelated control allows for the control of differently colored (e.g., red, green, and blue for RGB output) or similarly colored (e.g., white, blue, UV) LED dies.

Fig. 9B shows an example control circuit 305 that can provide pixelation to the array of LED dies contained in the solid state light device. In this example, sixty LED dies (LD1-LD60) are provided in the LED die array, which are grouped into three large groupings (314A – 314C) of twenty LED dies each, which are each further divided into smaller subgroups or channels (e.g., LD1-LD5) of five LED dies each. Overall, twelve channels of five LED dies each can be separately controlled in this exemplary embodiment. In one example implementation, in an RGB output application, a first grouping of LED dies can comprise red emitting LED dies, a second grouping of LED dies can comprise blue emitting LED dies, and a third grouping of LED dies can comprise green emitting LED dies. Alternatively, in another example implementation, first, second, and third groupings of LED dies can comprise "white" emitting LED dies.

In addition, the interconnect circuit layer is also designed to provide separate interconnection for the different LED die groupings. Different types of LED die groupings, and greater or lesser numbers of LED dies, can also be utilized in accordance with the principles described herein. With this configuration, separate RGB LED die channels can be driven to provide "white" or other colored output. In addition, should a particular diode channel fail or be dimmed due to LED die deterioration, adjacent channels can be driven at higher currents so that the output illumination appears to remain unchanged. Because of the (relatively) wide LED die spacing and/or the thermal management capabilities of the interconnect layer, greater drive currents to some of the LED die channels will not adversely affect overall performance.

In more detail, a voltage is provided to circuit 305 through power supply 306. The voltage is converted into a regulated output current/voltage supply by boost converter chips 312A – 312C, and their associated electronics (not shown). In this manner, voltage variations from power source 306 can be mitigated, with the current/voltage supplied to the LED dies being maintained at a regulated level. Chips 312A-312C can comprise, e.g., LM2733 chips available from National Semiconductor. In this exemplary embodiment, driving voltage/current parameters can be about 20 Volts at 80 – 100 mA, thus providing a total of about 1.0 to 1.2 A for the entire LED die array. The driving current/voltage is then supplied to

the different LED die channels within the array. In this example, each LED die would nominally require about 20 mA bias current, with a bias threshold increasing as the current increases, approaching about 4.0 V for a typical GaN-based LED die. Of course, differing LED die efficiencies or compositions may require differing bias and driving levels.

In addition, a resistor/thermistor chain 316 can be included in circuit 305 to set the overall maximum current for each LED die channel. Further, a switch set 318, comprising a corresponding number of LED die channel electronic switches, can be provided, whereby each LED die channel is coupled/decoupled to ground (or to power, depending on the LED orientation with respect to the switch set 318) in order to activate each particular LED die channel. The switch set 318 can be automatically controlled by a microcontroller (not shown) or a remote switch (e.g., a turn signal), based on the illumination parameters required for a particular application. Of course, this circuit architecture permits many implementations and permutations, as would be understood by one of ordinary skill in the art given the present description. For example, the control circuit 305 can be implemented to drive all LED dies with the same current, or alternatively, a given LED die channel can be turned on/off automatically or on command. By adding a fixed or variable resistance to the switch legs of the switch set, differing currents can be applied to each channel.

Fig. 10 shows a schematic illustration of an exemplary solid state light device 401 utilized in a lamp application that can be used for spot-curing. For example, solid state light device 401, which can be configured in accordance with the embodiments described above, is disposed in a compartment 402. Light device 401 can be secured in compartment 402 through the use of slidably engaging flanges 439 that are configured to slide and lock within slots 438 of a receptacle. Thus, the heat sink 440, which draws heat away from the direction of light output is located in a separate compartment 404. The beam-shaped output illumination can be collected/focused into a requirements-based illumination pattern by an optical element 415. Optical element 415 can be designed to provide a selected output pattern that complies with applicable standards. Example optical elements can include aspheric/anamorphic optical elements, and/or discontinuous and/or non-analytic (spline) optical elements.

With this approach, the use of complicated reflection optics disposed in compartment 402 can be avoided. In addition, as heat is drawn away from compartment 402, there is no need to specially heat-treat any remaining optical elements in compartment 402, thus avoiding potential performance degradation caused by exposure to continual high intensity heat. Further, if solid state light device 401 is provided with an output fiber and output aperture structure such as shown above in Figs. 6A-6C, steerable output illumination can be accomplished without having to utilize moving mirror, bulb, and/or lens mechanisms that currently must be employed when steering the output from conventional HID lamps.

The solid state light device described herein may also be utilized in other applications. For example, Fig. 11 shows a schematic highly-localized (e.g., dental) curing application, where solid state light device 501 (having a similar construction to that shown in Figs. 1A and 1B, and/or other embodiments herein) is contained in curing apparatus 500. The solid state light device 501 can be disposed in a handle portion 510 of curing apparatus 500. In addition, the output fibers used to receive and guide the output from the LED dies or other solid state light generating sources may extend through a light delivery arm 525 that can be placed directly over the curable material. In this application, UV and/or blue radiation sources may be utilized depending on the curing aspects of the materials receiving the illumination.

In an exemplary embodiment shown in Fig. 12, a schematic material-curing apparatus, such as a web curing station, is provided. For example, in adhesive, tape, or web-based manufacturing, the radiation-curable agent is often a blue/UV curable material that must be cured on a different material or substrate. In conventional methods, high intensity discharge, arc lamps, and microwave-driven lamps are often utilized to perform the curing process. However, these conventional lamps radiate light and heat in 360 degrees and therefore require complicated heat exchange and/or cooling mechanisms. Alternatively, the substrate material and UV curing agent must be adapted to withstand high intensity heat in some conventional approaches.

A solution to the heating problems found in conventional curing systems is schematically illustrated in Fig. 12, where a curing station 600 comprises a solid state light device 604 (constructed similarly to those embodiments described above, such as in Figs. 1A

and 1B), where the heat dissipation or heat sink component of the solid state light device can be coupled to or replaced by a heat exchange unit 602. As discussed above, heat generated by the radiation sources of the solid state light device is drawn away from the direction of the light output by proper LED die spacing, thermally conductive interconnect circuitry, and/or heat sinks. Curing station 600 can be utilized for continuous curing operations and/or for piece parts, spot curing, or sheets.

In addition, solid state light device 604 can deliver highly concentrated radiation to radiation-curable materials, thus reducing the deleterious effects caused by poor depth of cure, which may be evident when using conventional LED arrays for radiation curing. For example, as is described above with respect to Figs. 1A, 1B, and 2, the LED die footprint can concentrated to a fraction of the original LED die array area. For example, the footprint of the output ends can be a factor of 2-5 times smaller than the footprint of the LED die array, with a corresponding intensity increase (including coupling losses) per unit area at the end of the fiber array. For example, each LED die can be a GaN-based LED die with an output power density approaching 100 mW/cm^2 per die of nominal 365-nm radiation. A resulting irradiance value can approach, or even exceed, the output of a conventional high power (600 W/in), focused mercury ultraviolet lamp, which typically outputs about 2 W/cm^2 of nominal 365-nm radiation.

The concentrated output of the LED dies or other radiation-generating source can be collected and guided by the waveguide array, disposed in strain relief housing 630, and delivered to a radiation-curable material or formulation 650. Radiation-curable materials can include, for example, acrylate or epoxy monomers and/or oligomers, with a suitable photo-initiator or blend. The radiation-curable material or formulation 650 can be disposed on a substrate 652. Example substrates can include continuous polymer, textile, metallic foil, and the like.

The substrate 652 can be disposed on a platform, such as a moving platform or conveyor belt, or substrate 652 can be suspended between moving rollers (not shown), to provide for sheet or continual curing of large quantities of material. As mentioned above with respect to Figs. 5A-5F, the output ends of the waveguides, e.g. optical fibers, can be arranged

in a number of different reconfigurable patterns, thus making the solid state light device particularly suited for curing materials having a wide variety of shapes, and/or curing depth requirements.

For example, as mentioned above, the output ends of the fibers can be arranged in a selected pattern. In curing applications, selected patterns can be chosen to provide for curing of piece-part substrates having corners, crevices, and other structures that do not receive uniform curing radiation from conventional "flood"-type sources. In this manner, shadow effects can be reduced by proper arrangement of the output ends of the fibers.

In addition, apparatus 600 can further comprise a controller 670 that is coupled to solid state light source 604. Controller 670, which can be implemented as a single controller unit or as a set of controller units, can be adapted to selectively activate different LED dies of the LED die array to emit radiation corresponding to preferential absorption bands of exemplary photo-initiators and/or to cure different types of formulations. For example, controller 670 can include multiple different control sections (for example, control sections 670a –670d) that correspond to different LED die sections or individual (independent) channels within the LED die array of solid state source 604. Alternatively, multiple, independent controller units can be used to control each LED die channel individually. The control can be accomplished using electrical or mechanical switching, e.g., using toggle switches (not shown).

Each LED die section can comprise, for example, a set of LED dies that emit radiation at a different wavelength from the other sets of LED dies and/or irradiate a different section of the radiation curable material 650. Using the exemplary pixelation circuitry described above, apparatus 600 can thus provide greater flexibility in curing different types of materials using the same curing device. For example, one or more groups of the LED dies can be selectively activated, e.g., switched on or off, to accommodate one or more photoinitiator(s) in the curable material.

In this exemplary embodiment of the present invention, emitted radiation from a plurality of solid state sources can be concentrated into a predefined pattern such that an irradiated surface receives much higher intensity than could otherwise be attained with said sources located in close proximity to each other and said irradiated surface. The above-

described curing apparatus can be utilized for continuous substrate, sheet, piece part, spot curing, and/or 3D radiation-cure processes.

As compared to conventional curing devices that use lamps, the curing apparatus 600 of Fig. 12 may provide longer lifetimes, less power requirements, greater efficiency, small form factors (for tight clearance cure applications), with little or no emitted infrared radiation to the substrate and/or chemistry (which is of particular importance for heat-sensitive product constructions).

According to this exemplary embodiment of the present invention, high irradiance levels can be attained from short wavelength (<500-nm), lower intensity LED dies through the use of optical concentrating elements coupled with optical waveguides, whose output can be selectively patterned. In this manner, shorter wavelength LED dies can be utilized without suffering from conventional low irradiance problems. In addition, a wide range of photoinitiators and photoinitiator blends can be used in the curing material 650. Example photoinitiators can include ITX and Camphor Quinone (available from Biddle-Sawyer), TPO-L (available from BASF), and IRGACURE and DAROCUR series initiators (available from Ciba Specialty Chemicals).

Also, by using the above-described optical fiber-concentrator construction, LED dies can be spaced apart at distances (e.g., at least 6 die widths or greater) that are suitable for straightforward thermal management and electrical connections. The resulting efficient heat dissipation can effectively extend the lifetimes of the LED dies and maintain higher irradiance. In addition, current/power driving requirements per LED die can be reduced without affecting irradiance levels, as more LED dies can be utilized within a relatively small footprint. Thus, longer overall die lifetime can be achieved according to exemplary embodiments of the present invention.

A problem associated with low irradiance is that if irradiance is too low, the rate of cure towards the bottom of a relatively thick radiation-curable formulation is reduced. Therefore, depth of cure and adhesion can become problems with some conventional LED-based approaches. Problems with depth of cure are intensified if the formulation contains scattering centers or radiation absorbing particles, pigments, or dyes. Moreover, further

problems can arise if the radiation must pass through a carrier film or a roll before reaching the formulation.

As a solution, apparatus 600 can further include a lens or a plurality of lenses can also be formed integral with (e.g., fiber lenses) or placed separate from the ends of the fibers to further concentrate or collimate the radiation to the material or formulation being cured. Such lenses can facilitate the curing of relatively thick and/or high absorption and/or scattering formulations and for orientation of a component(s) within the irradiated formulation. For example, a lens or lens array (not shown) can be disposed at a selected distance from the output ends of the fibers/waveguides. As mentioned previously, as the heat generated from the radiation sources is drawn away from the direction of emission, the additional output collimating/focusing lenses need not be specially treated for continual heat exposure.

In addition, according to this exemplary embodiment of the present invention, apparatus 600 can provide a more uniform curing beam by extending a concentrated pattern into a cross-machine direction (CMD) and/or machine direction (MD) array. In conventional lamp-based systems, lamps have at least 15% variation across their lengths. In some cases, the uniformity variation for lamps can degrade to 30-40% over time. In conventional LED-based approaches, LEDs in an array are separated such that separation leads to irradiance non-uniformity across the array. This non-uniformity can cause potentially detrimental effects on the final product properties due to uneven cure.

The curing apparatus of the present invention can also utilize an array of LED dies of different types that can be controlled through the pixelation circuitry described above in Figs. 9A and 9B. For example, since the output ends of the fibers can be tightly coupled, different types of LED dies (e.g., of varying intensity and/or wavelength) can be incorporated into the LED die array, thereby creating a wavelength and/or intensity-selective curing apparatus, with minimal loss in uniformity in the machine- and cross-machine directions. In addition, incorporating different wavelengths of LED dies into the LED die array may be utilized to emit radiation at selected wavelengths coinciding to preferential absorption bands of exemplary photo-initiators such as, e.g., a blend of ITX and TPO-L.

Thus, curing apparatus 600 can be designed to cure with different wavelengths and/or intensities so that the same curing apparatus can be used to cure different types of formulations, making apparatus 600 suitable for laboratory, pilot, and production lines that process different formulations that require different radiation wavelengths and intensities. In addition, with the pixelation controller circuitry described herein, apparatus 600 can be controlled to selectively activate particular LED dies or LED die groupings depending on the type of material being cured. In contrast, with conventional approaches, a LED array is usually configured with only one particular type of LED. Thus, when a different wavelength or intensity is needed with a conventional system, a new array is required to accommodate the formulation absorption. This leads to additional modules that require more equipment costs and more potential maintenance.

Apparatus 600 is also suitable for high resolution curing of patterns, 3-dimensional structures, lithography, and masking. For example, as the output ends of the fibers can be secured in a reconfigurable banding, such as banding 156 from Fig. 1B, the output ends of the fibers can be arranged into a pattern to cure a particular 3-dimensional structure and/or part. For substrate-based processes, apparatus 600 can provide high-resolution irradiance profile curing in the cross-machine and machine directions. As the output ends of the fibers may be tightly bundled or tightly patterned, the LED dies may be driven at varying intensities to create a uniform intensity profile, with resolution being on the order of the fiber diameter. In contrast, conventional LED arrays that are spaced further apart (for thermal purposes) provide a more discontinuous intensity profile.

While the present invention has been described with a reference to exemplary preferred embodiments, the invention may be embodied in other specific forms without departing from the scope of the invention. Accordingly, it should be understood that the embodiments described and illustrated herein are only exemplary and should not be considered as limiting the scope of the present invention. Other variations and modifications may be made in accordance with the scope of the present invention.